REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
31-07-2016

2. REPORT TYPE
final

3. DATES COVERED *(From - To)*
May 2013 - Apr 2016

4. TITLE AND SUBTITLE
Predictions of bedforms in tidal inlets and river mouths

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-13-1-0621

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Edith L Gallagher

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Franklin and Marshall College

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A: Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The objective of the proposed study was to use a self-organization model to predict bedforms in tidal inlets and river mouths. Specifically, an existing model would be further developed and used to predict multiple scales of bedform formation, growth, adaptation and migration. Predicted bedforms would be used to predict time-varying, dynamic roughness and friction factors to inform larger scale hydro- and morpho-dynamic models. Results suggest that multiple scales of bedforms exist simultaneously, complicating the interpretation of bed roughness. In addition, model results and data in the literature suggest that temporally varying flow results in temporally varying roughness.

15. SUBJECT TERMS
Bedforms, hydraulic roughness, tidal inlets, rivers

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
u	u	u	uu		Edith L Gallagher
					19b. TELEPHONE NUMBER *(Include area code)* 717-291-4055

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PREDICTIONS OF BEDFORMS IN TIDAL INLETS AND RIVER MOUTHS

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Award Number: N00014-13-1-0621

LONG-TERM GOALS

The long-term goals of this research have been to model bedforms in tidal inlets and river mouths. To do this, an existing self-organization bedform model has been used. The advantages of this model are that it is relatively simple, with intuitive rules for transport and feedback, it is easily adaptable and produces realistic results. Results from this model have been used to examine bedform growth and dynamics as well as resulting bedform-induced roughness parameterizations.

OBJECTIVES

The specific objectives of this study have been to

- develop and adapt the present model for flows in river mouths and tidal inlets, including expanding the model to 2-D in morphology, transport and flow modules, scaling the model up for larger spatial domains and translating to FORTRAN for faster runtimes.
- test the hypothesis that bedforms grow and adapt continuously and because of this, multiple scales of bedform formation, growth and migration can occur simultaneously.
- compare model predictions with measurements from the literature, from the Hampton River Inlet (Lippmann), from the Golden Gate (Hanes), from the New River Inlet Experiment (Lippmann, Traykovski) and from the Columbia Rive Mouth (Traykovski).
- calculate bed roughness parameterizations useable by hydro- and morpho-dynamic modelers.
- work with the CSDMS so that the present model can be utilized by that community modeling environment.

APPROACH

Bedforms are ubiquitous in unconsolidated sediments. They act as roughness elements, altering the flow and creating feedback between the bed and the flow and, in doing so, they are intimately tied to erosion, transport and deposition of sediments (eg Parsons et al. 2005, Ernstsen et al. 2005). It has been suggested that bedforms in rivers and tidal inlets are dynamically similar to Aeolian dunes and bedforms on the continental shelf and in the surf zone (Best 2005, Frank and Kocurek 1996, Nemeth et al. 2007, Gallagher 2003). Because of this similarity, Gallagher (2011) developed a model for bedforms in the nearshore, based on the principles of work by Werner (1995), who hypothesized that Aeolian dunes were self-organized features and as such could be modeled with a relatively simple model.

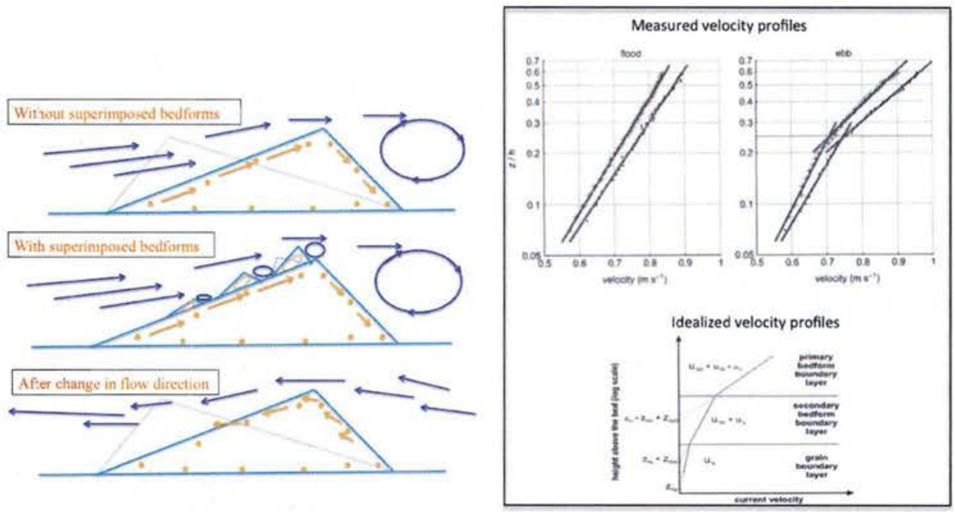
It has been suggested that self-organization is responsible for the formation of many different types of morphological patterns. Werner (1995) used a 'hierarchical' approach (Ahl & Allen 1996) to modeling self-organized systems, wherein processes at different temporal and spatial scales are distinct from each other and can be separated. With this approach, grain-scale sediment transport is parameterized with simple rules to drive bedform-scale dynamics. Gallagher (2011) developed a similar model to predict nearshore, combined flow megaripples. The model consists of a matrix of sediment slabs that represent a spatial domain or a region of a bed across which sediment is moving. The sand slabs are picked up and moved according to a transport model (either simple rules similar to Werner (1995) or a physics-based formulation, e.g. Bailard 1981, Ribberink 1998). Sediment transport is driven by the free stream velocity, u, which can be modeled with a sinusoidal velocity, a measured velocity signal from the natural surf zone or with a Rayleigh distributed wave velocity signal. In the original model, for each time step, the flow is the same at all locations in the domain except for an imposed random spatial fluctuation representing local turbulence. However, once bedforms are created, the local flow around the bedforms is altered via feedback: flow is reduced in the lee of a bedform to simulate a velocity shadow zone and flow is accelerated over the crest of a large bedform. These spatial alterations to the flow generate gradients in transport, which alter the bed. Feedback is required for bedform growth and development (Gallagher 2011). In addition, the slope of the bed is not allowed to exceed 17^{o}.

The long-term plan for this research has been to use the self-organization model, originally developed for nearshore bedforms, and to adapt it for predicting bedforms in the combined flows of tidal inlets and river mouths. In these environments, oscillatory flows with wave frequencies are superimposed on the quasi-steady flows associated with tides (oscillatory but with a much longer period than the surf waves) as well as steady flows (possibly with seasonal variations) exiting river mouths. These complex, but naturally realistic, flows have been incorporated to predict the growth and migration of dunes and the evolution of multiple scales of bedforms. This model lends itself to tackling these dynamically complex issues, because relatively simple changes can be implemented to test the importance of factors such as lateral flows, feedback changes, grain size and subtle 3-D morphology changes. Model results have been compared with data from the literature (eg, Hanes 2012 , Jerolmack and Mohrig 2005, Ernstsen et al. 2005, Lefebvre et al. 2013) and with data collected as part of the River Mouths and Tidal Inlets DRI experiments in collaboration with Tom Lippmann (UNH), Steve Elgar (WHOI) and Peter Traykovski (WHOI).

WORK COMPLETED

Bedforms will grow until some aspect of the environment limits their growth, like the water depth or changes in the flow field (Clarke and Werner 2004, Gallagher 2011). In April 2015, at the ONR program review, Peter Traykovski presented a geometric model for the time required for a bedform to change shape and orientation under tidally varying flows (represented as a 180 degree change in flow direction). That adaptation time is related to the size of the bedform: the larger the bedform, the longer it takes to adapt (Fig 1, left panels, solid line to dashed lines) simply because there is more sand to move. Larger-scale features are often observed to maintain their orientation under alternating tidal flows (eg, Lefebvre et al. 2013) because large features need more time to re-orient than is available in a tidal cycle. Generally, it is presumed that large features with fixed orientation indicate the dominant flow direction. Fixed orientation also could be owing to vertical or horizontal flow differences on the ebb and flood, such that the bedforms do not experience strong flows in both directions. In these cases as well as asymmetric flows, the time required to re-orient plays an important role.

In many natural tidal inlets, bedforms fields often have two scales of bedforms (the Golden Gate, CA, Barnard et al. 2006; the Marsdiep Inlet, NL, Buijsman and Ridderinkhof 2008; in the North Sea and many other locations). Recent papers by Lefebvre et al. (2011, 2013) document smaller-scale features changing direction while larger scale features remained ebb-oriented in the Jade Inlet in Germany and in the Knudedyb Inlet in Denmark. Because smaller bedforms can change shape more quickly, superimposed smaller-scale features will respond to changing tidal flows, while the larger-scale features beneath do not.



From Lefebvre et al. 2013

Figure 1. Left panels: illustration of bedforms, showing flow and separation zones over steep lee faces. Also suggested is the volume of sand to be adjusted such that the bedform can be re-oriented when the flow changes direction (dashed lines, following Traykovski's work April 2015). Until that re-orientation takes place, bedform induced roughness will be reduced (Lefebvre et al. 2013) because the downstream faces are not yet steep enough to cause flow separation. Right panels, all from Lefebvre et al. (2013). Top two panels: observations from the Knudedyb Inlet of different boundary layers over bedforms with different symetries with respect to the ebb and flood currents. During the flood, only smaller bedforms are 'felt' by the flow and roughness is low. During the ebb, two boundary layers appear, one owing to large bedforms and one owing to small bedforms. The large bedform increase the roughness by an order of magnitude. Bottom: schematic showing boundary layer changes owing to different scale bedforms.

Lefebvre et al. (2013) measured velocity profiles over the bedforms and found that the velocity profile shape and therefore the bedform-induced roughness were quite different during the ebb and flood phases (Fig 1, top right). This was attributed to the asymmetry and steepness of the bedforms encountered by the flow. Bedforms with a steep lee slip-face cause flow separation (Fig 1, left top) and this increases the bedform-induced roughness. Conversely, bedforms with no steep lee slip-face (with respect to the flow direction) do not cause flow separation (Fig 1, left bottom) and therefore impose less drag on the flow. In addition, Lefebvre et al. (2013) hypothesized that multiple boundary layers could be present owing to bedforms of different sizes (Fig 1, bottom right).

Taken together, the time history of bedform shape over a tidal cycle and the control that shape has on the bedform induced roughness suggests that bed roughness will go through a range of roughness values over a tidal cycle. Fig 2 shows an idealized roughness time series created by following the observations of Lefebvre et al. (2011, 2013). During the flood tide, the larger bedforms do not re-orient themselves with the tide, so flow separation does not occur in their lee. In this case, roughness is dominated by smaller features that do re-orient themselves and cause flow separation on a smaller scale. However, during the ebb tide, there is separation and drag over the larger bedforms, thus bed increasing roughness.

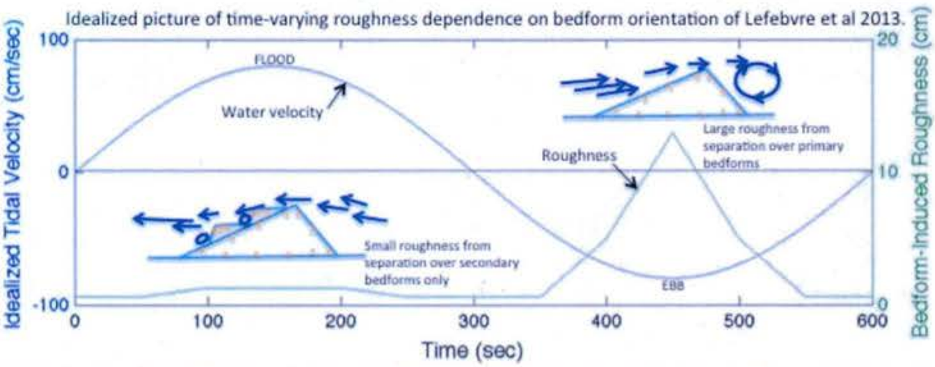


Figure 2. Idealized picture of time varying roughness over a tidal cycle taken from the observation of Lefebvre et al. (2013). When bedforms are oriented with the flow, their down-stream steep slipface causes flow separation which increases the bedform induced roughness and changes the velocity profile (during the ebb in this picture). When the flow is against the large bedforms (during the flood), their smoother lee slope does not induce flow separation or higher roughness. However, smaller scale bedforms can re-orient themselves and cause flow separation, increasing roughness slightly (less owing to their smaller size). So, in this scenario, roughness is lower during the flood tide than during the ebb tide

RESULTS

The present model is being used to examine the development and the temporal evolution of primary and secondary bedforms as a function of flow characteristics and water depth (the two factors that Sterlini et al. 2009 said were most important). The present model does not accurately represent the vertical flow profile above the bedforms. However, using the modeled bedforms' shape, inferences about the time-history of the drag over changeable bedforms can be made. Following the observations of Lefebvre et al. (2013), if a bedform is asymetric in the downstream direction, with a steep lee slipface, then it will cause flow separation and it will generate more drag on the flow, thus the bedform-induced roughness will increase dramatically (an order of magnitude). If a bedform is not oriented with the flow and/or its slopes are gentler (less than 10-15 degrees, Paarlberg et al. 2009), then they do not induce separation and they appear smoother to the flow.

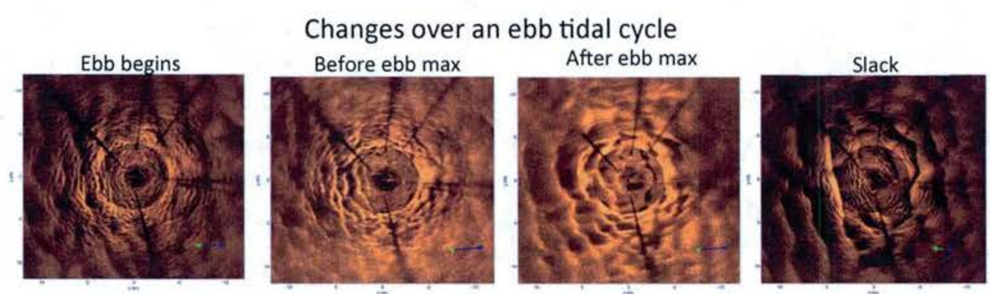


Figure 3. Examples of bedforms from side scan sonar images from the New River Inlet experiment (Traykovski). The four panels are from a single ebb tide and suggest a change in orientation from flood dominated (left) to ebb dominated as well as changes in existence and magnitude of secondary features. Dark brown color indicates acoustic shadows and lighter colors indicate surfaces sloped toward the sonar. Outward rays are shadows of the sensor platform.

In contrast to Lefebvre et al., observations from the New River Inlet (Fig 3, from Traykovski) show dramatic bed changes over a tidal cycle. These bedforms are 1-3 m lengths and exist most of the time. However, they change orientation with the tidal flow, they sometimes have superimposed, smaller-scale bedforms, and they are sometimes smoothed or even wiped out. These highly variable, smaller scale features are in shallow water (~2m) and generate their own variable roughness time series, including increased roughness owing to secondary bedforms and reduced roughness when features are reorienting and there is no lee slip face and flow separation. Figure 4 shows modeled results that are similarly variable to those in Fig 3. The four sets of panels illustrate changes in bedforms from one slack period to the next. Near slack tide (t=19200s, top panels in Fig 5) the model predicts a bed where large bedforms (oriented to the left) have been smoothed by the waning water velocities. This is similar to the third panel in Fig 3. As the tidal flow begins to pick up strength in the opposing direction, the existing bedforms begin to reverse direction and secondary features start to build (t=19320s, second panel, Fig 4, similar to left panel in Fig 3). In the third panel (t=19450s in Fig 4), the strong flows have helped to build the secondary features (similar to second panel in Fig 3). (Note that the model makes bedforms too tall and peaky when flows are strong. This is owing to anomalously large transport gradients at the bedform crests, because there is no sediment suspension and bypassing in the present simplistic model.) As the tidal flows wane again the large features are smoothed and the underlying bedforms again are visible. This series of images (Fig 4) is similar to what is observed in the natural tidal inlet (Fig 3).

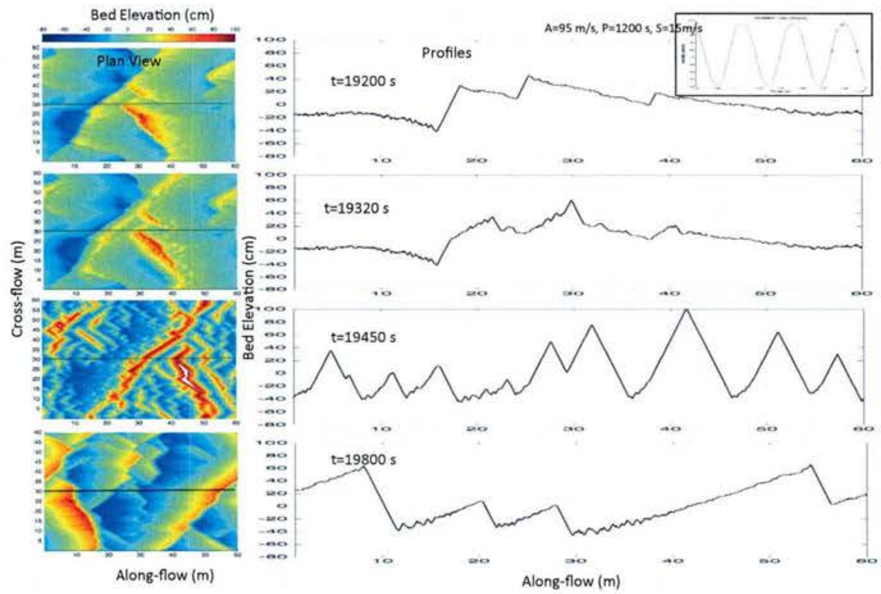


Figure 4. Modeled bedform time series over a single ebb tidal cycle (asterisks in small top panel indicate time in the cycle). Left panels show plan views of beds, right panels show profiles along black line in left panels. Large bedforms with wavelengths of about 15 to 20 m have formed, but are broken down and reformed with each tidal cycle (similar to observations Fig 3). The time series of roughness can be estimated from bedform predictions like these. (Note, peaky bedforms in panel 3 are anomalously high, see text.) Conditions are steady flow, S = 15 cm/sec, oscillatory flow amplitude, A=95 cm/sec, tidal period, P=1200 sec. Positive velocity is from left to right. This model run was for 20000 secs.

Traykovski (2016) examined similar bedforms from the Columbia River Mouth experiment. He estimated the asymmetry of the bedforms and found that changing bedform asymmetry lags behind the change in water direction (Fig 5, from Traykovski), owing to bedform reorientation (as in Fig 1). A similar analysis on modeled bedforms was performed and Fig 6 (top) illustrates the calculation that was used to generate a proxy for roughness. This proxy includes the slope (which, in nature, generates flow separation), the height (which dictates the magnitude of the separation) and the water velocity (without which there is no roughness effect).

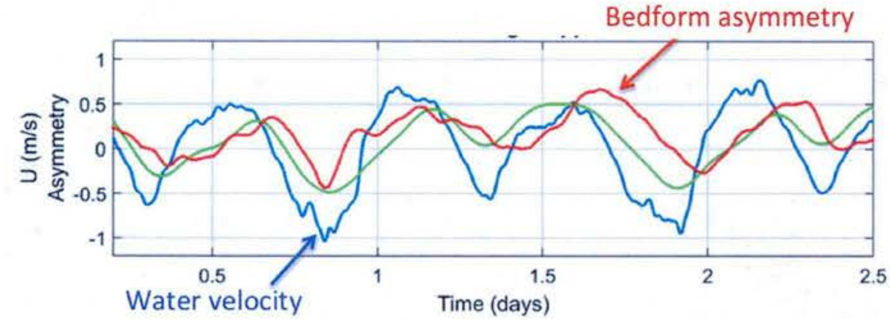


Figure 5. Measurements from the Columbia River Mouth Experiment (from Traykovski). Water velocity (blue) and bedform asymmetry both change directions with the tide, but the asymmetry lags behind the forcing flow by a couple of hours.

The bottom two panels in Fig 6 show the modeled velocity time series and the roughness proxy. Similar to Traykovski's observations, the bedform induced roughness lags behind the forcing flows. Results like this are encouraging and it is expected with a few model improvements, the correspondence with the observations will be better and our understanding of bedform growth, development, adaptation, sediment transport and roughness will all be informed and improved. Using model results, roughness time series can be constructed and compared with measurements of roughness from velocity profiles. From this understanding, fluid flow models can be improved with predictions of time varying roughness. In addition, the model has the potential to allow larger scales and slower temporally varying features to be predicted and their effects on transport and flows to be investigated.

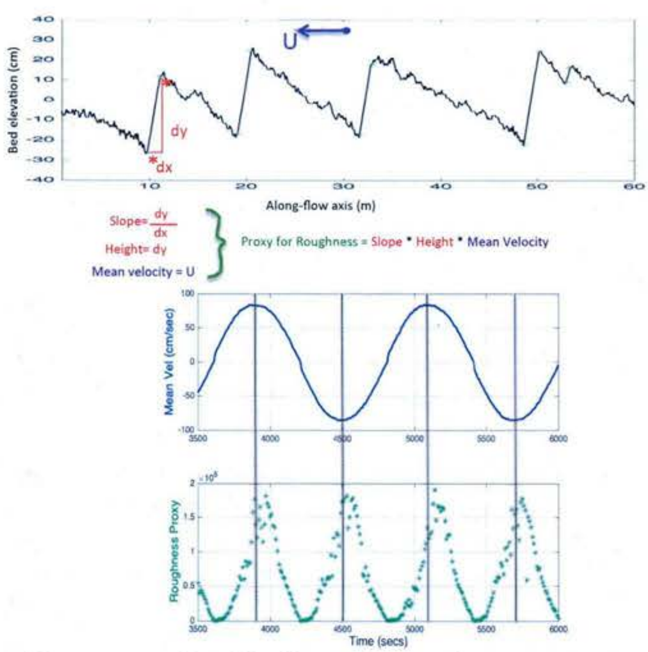


Figure 6. Top, profile across predicted bedforms showing the parameters used for the roughness proxy and the calculation (dx and dy were estimated via Matlab using hand picked points). Bottom two panels show the water velocity and the roughness proxy for tidally varying predicted bedforms. Similar to observations (Fig 5), the bedforms lag behind the fluid forcing.

Adaptation of the model feedback is being tested to create more realistically shaped bedforms and to improve the predicted bedform shape, slope and therefore bedform-induced roughness. One adaptation would be to change the calculation of slope, which is done locally now. Calculation of slope on the scale of a bedform would allow for feedback at bedform scales, rather than at "grain" or block-scales.

Also, a simplified mechanism for suspended load bypassing is being developed in the feedback/transport routines to improve modeled bedform crest shape. These changes are being tested, always with an eye toward keeping the model concepts simple and fast.

IMPACT/APPLICATION

This model was developed for the nearshore and is now being applied to different environments. It is being used with some success to predict tidal inlet bedform morphologies. From these predictions, estimations of time varying hydraulic roughness are being made. This has been first attempt at modeling tidal inlet and river mouth bedforms with the self organization model and a first attempt at predicting time varying roughness. It is expected that a simple model of this type can be used to estimate bedforms and roughness in a variety of flow environments. The model is available on CSDMS and it could be easily integrated into larger-scale flow and morphology models and will help improve the predictive capabilities of hydro- and morpho-dynamics in general.

RELATED PROJECTS

This work was originally supported by an NSF ADVANCE grant. ONR was the only granting agency for this work until recently. Currently this work is not funded.

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PUBLICATIONS

Abstracts and Presentations

Gallagher, E.L., Computer Simulations of Bedforms and Roughness in Tidal Inlets and River Mouths. Abstract and presentation at the AGU Ocean Sciences Meeting, New Orleans, LA, Feb 2016.

Gallagher, E.L., Prediction of Bedforms and Roughness in Steady, Tidal and Oscillatory Flows. Paper and presentation at the Marine and River Dunes Symposium, Caenarfon, Wales, April, 2016.

Peer-reviewed Publications

Reniers, A, E.L. Gallagher, J.H. MacMahan, J.A. Brown, A.A. van Rooijen, J.S.M. van Thiel de Vries and B.C. van Prooijen. (2013) Observations and modeling of steep-beach grain size variability. *Journal of Geophysical Research Oceans*, 118, 1-15, doi:10.1029/2012JC008073 [published, refereed].

Brown, J.A., J.H. MacMahan, A.J.H.M. Reniers, E.B. Thornton, A.L. Shanks, S.G. Morgan, E.L. Gallagher. Mixing and transport on a steep beach. *Continental Shelf Research*, accepted 2014. [accepted, refereed].

Gallagher, E.L. (2016) Predictions of bedforms and bedform induced roughness in tidal inlets. In prep.